

# AN EXPERIMENTAL STUDY ON THE APPLICATION OF SINGLE-PHASE ULTRASONIC FLOWMETER IN THE STRATIFIED HORIZONTAL TWO-PHASE FLOW

**J.L.H. Faccini, P.A.B. De Sampaio**

Nuclear Engineering Institute  
Brazilian Nuclear Energy Commission (CNEN)  
CP 68550, Rio de Janeiro, 21941-972, Brazil  
[faccini@ien.gov.br](mailto:faccini@ien.gov.br), [sampaio@ien.gov.br](mailto:sampaio@ien.gov.br)

**J. Su**

Nuclear Engineering Program, COPPE  
Universidade Federal do Rio de Janeiro  
CP 68509, Rio de Janeiro, 21945-970, Brazil  
[sujian@lasme.coppe.ufrj.br](mailto:sujian@lasme.coppe.ufrj.br)

**Abstract.** *This paper describes an experimental work conducted in order to investigate a hybrid ultrasonic technique suitability for measuring a two-phase gas-liquid stratified flow in horizontal pipes. The experiments involve the use of a single transducer pulse echo technique and an industrial contrapropagating clamp-on ultrasonic flowmeter for liquids. The single transducer pulse echo technique consists in installing a single ultrasonic transducer at the bottom of a horizontal pipe, where a two-phase gas-liquid stratified flow is occurring. One part of the ultrasonic pulse discharged from the transducer will be transmitted through the liquid and then reflected back from the liquid-gas interface. By measuring the transit time of the reflections it is possible to determine the liquid level. For the ultrasonic flowmeter an ultrasonic signal, coming from a first ultrasonic transducer placed upstream outside the pipe wall, and travelling wholly through the liquid phase of the two-phase stratified flow with an inclination angle relative to the cross section of the pipe, is reflected by the interface between the liquid and gas. After this reflection it follows to a second ultrasonic transducer downstream at the same side of the first one. Then, the liquid velocity is averaged along this path by the ultrasonic flowmeter. To convert this velocity in a velocity averaged along the cross section occupied by the liquid, a correction factor is required. Based on this configuration, a physical-mathematical model based on the Reynolds Averaged Navier-Stokes is used to obtain the complete velocity field in the flow. Thus, the velocity component in any ultrasonic path, detected by the ultrasonic flowmeter, can be determined numerically as well as the liquid level. From this procedure, a correction factor emerges as a relation between the averaged velocity in an arbitrary cross section occupied by the liquid, and the averaged velocity along the ultrasonic path. The experimental results are compared with the numerical calculations in order to check the hybrid ultrasonic technique employed and its potential as a useful device for measuring the two-phase gas-liquid stratified flows.*

**Keywords:** *ultrasonic technique, ultrasonic flowmeter, two-phase flow, stratified flow, numerical model*

## 1. INTRODUCTION

In spite of the great development experienced by the multiphase flow measurement techniques in the last decades, specially in instrumentation and in electronics, currently it remains a technical challenge to be overcome by researchers and engineers. The difficulties arise from the fact that the flow varies considerably over the pipe cross section due to its fluctuating nature, and from the wide variety of flow regimes which are possible in multiphase flow in horizontal, inclined and vertical pipes.

Beside the void fraction, the flow rate is a fundamental parameter to describe the multiphase flow behaviour aiming to development of physical models to predict mass, momentum and energy transfer. However, much of the research and the development of multiphase flow measurement is devoted to the needs of a large amount of practical applications in the nuclear engineering, oil and gas pipelines and in a whole spectrum of industries.

The use of single-phase flowmetering for two-phase gas-liquid flow rate is an interesting emerging theme for academic/scientific research as well as for industrial practical applications. Many manufacturers and companies are now considering the possibilities of handling two-phase flowmetering applying the available single-phase technology. In this issue some of the latest works in Coriolis mass flow metering were due to Henry *et al.* (2000) and Liu *et al.* (2001), while Cha *et al.* (2002) and Cha *et al.* (2003) have reported investigations in electromagnetic flowmetering. Several patents are attempting to solve the problems associated with metering two-phase flow with dedicated ultrasonic flowmeters, Letton (2003), Vedapuri and Gopal (2003), Zanker (2004).

Henry *et al.* (2000) described in details a digital based Coriolis flowmeter for operation with two-phase flow and partially-empty tube conditions. In particular, the authors observed a large mass-flow measurements errors when the two-phase flow was in horizontal orientation, with lower gas and liquid flow rates. At higher flow rates, the results were

considered reasonable. They concluded that better corrections techniques must be developed to improve the understanding the effects of the two-phase flow over the measurements.

Liu *et al.* (2001) applied neural networks on the digital Coriolis single-phase mass flowmeter, described by Henry *et al.* (2000), in order to correct the errors induced by the presence of a two-phase flow. The authors could reduce the mass flow errors from as high as 20 % to within 2 %, but for a limited range of their own experiments in a horizontal 1 in. tube.

Cha *et al.* (2002) developed an electromagnetic flowmeter useful for two-phase flow. A series of experimental runs were carried out by authors to check the performance of the flowmeter under the vertical air-water bubbly and slug flow in a 1 in. tube. The main conclusion achieved by the authors was that the electromagnetic flowmeter showed a good performance to identify and to measure the flow patterns generated. Thus, Cha *et al.* (2003) extended their study to nitrogen-sodium mixtures in order to investigate the flowmeter behaviour in liquid metal two-phase flow.

Letton (2003) has registered a patent describing an ultrasonic flowmeter for stratified two-phase gas-liquid flow in horizontal pipes. The flowmeter is consisted of a three pairs of contrapropagating clamp-on ultrasonic transducers. According Letton (2003), by measuring the transit times between the transducers it is possible to obtain the phase velocities, the liquid level and the others two-phase parameters. Similar patents have been presented by Vedapuri and Gopal (2003) and Zanker (2004).

The purpose of this work is to investigate the application of a hybrid ultrasonic technique for measuring a two-phase gas-liquid stratified flow in horizontal pipes. The experiments involve the use of a single transducer pulse echo technique, an industrial contrapropagating clamp-on ultrasonic flowmeter for liquids and a physical-mathematical model describing the flow field, that can determine more comprehensive information such as liquid level and liquid flow rate simultaneously. The hybrid ultrasonic technique shall be applied to a stratified air-water two-phase horizontal flow.

## 2. EXPERIMENTAL SET-UP

### 2.1. Two-phase flow section

The two-phase flow section used in this work is already described by Faccini *et al.* (2004), and is shown in Fig. 1. The two-phase flow section is a 5.0 m long horizontal tube (stainless steel ) with an inner diameter and outer diameter of 51.2 mm and 57.0 mm respectively, followed by a short tube 0.6 m long transparent acrylic with the same inner diameter. The section operates with distilled water coming from an existing single-phase water loop which is equipped with a centrifugal pump and a metering rig. Air is injected into the mixer at the entrance of the two-phase flow section, through an air flow line equipped with appropriated air instrumentation. The air-water mixture goes out from mixer and travels through the horizontal tube along its length until the transparent acrylic tube where it can be measured and observed visually. The experiments are performed with air at 1.0 bar pressure and 25° C temperature conditions. The air flow rate is measured by a rotameter (uncertainty  $\pm 3\%$ ). A thermocouple is installed in the region of the air injector to measure the air temperature. The water flow rate is measured by a rotameter as well.

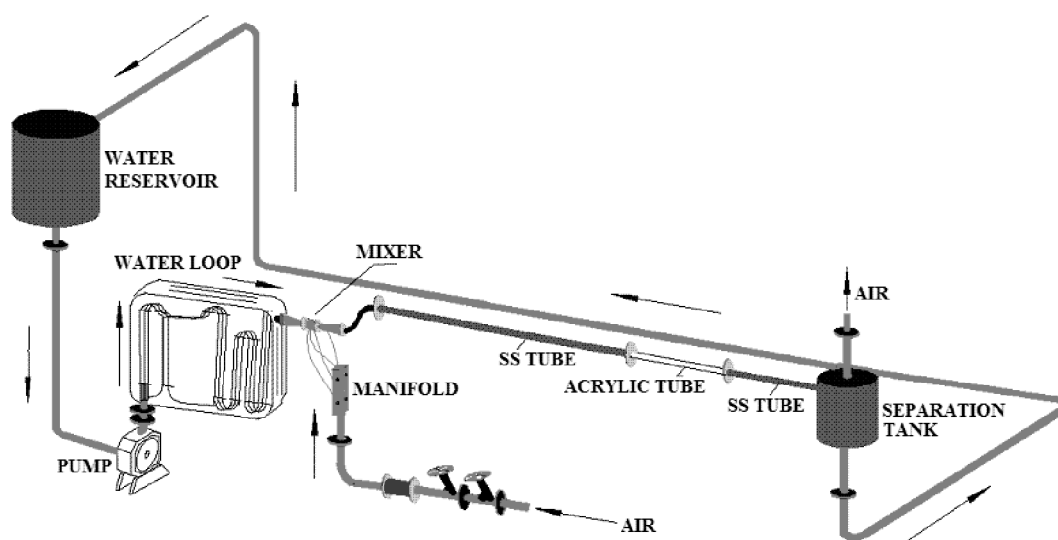


Figure 1. Two-phase flow section

## 2.2. Ultrasonic systems

In the two-phase flow section, the water flow rate was monitored by a contrapropagating transmission ultrasonic flowmeter (CPUF) placed at 10 diameters after the acrylic tube. The CUF system has two transducers attached to the outside wall of the flow section. The acoustic transmission between the transducers is indirect, that is, reflected twice by the interface air-water (W-path) and the transit-time method is used to measure the volumetric flowrate as in the case of single-phase flow (Ultraflux, 1998), (Lynnworth and Magori, 1999). The CUF system was made up of an ultrasonic flowmeter Ultraflux, model 600, connected to the data acquisition system of the single-phase water loop. The flowmeter signals were recorded in a computer at intervals of 1 s.

At the bottom of the acrylic transparent tube, one single transducer pulse-echo ultrasonic system (PEU) was installed for measurement of the water level inside the tube. One part of the ultrasound pulse discharged from the PEU is transmitted through the water and then reflected back from the air-water and wall-water interfaces. By measuring the transit time of these multiple reflections it is possible to determine the liquid level, (Chang *et al.*, 1982), (Matikainen *et al.*, 1986), (Chang and Morala, 1990), (Masala *et al.*, 2007). The PEU set-up is formed by one single longitudinal wave transducer Panametrics, model V112, 0.25 in. (6 mm) diameter and 10 MHz; a generator/multiplexer board Ultratek, model DSPUT5000; and a PC computer running a data acquisition software. The transducer was connected via cable in the board which was inserted into the computer PCI slot. The board was controlled by the software providing signal generation and data acquisition of the ultrasonic signals. A total rate of 53 Hz was estimated for the PEU to digitalize the ultrasonic signals and to calculate the transit times of them.

## 3. PHYSICAL-MATHEMATICAL MODEL

When an ultrasonic beam propagates in a moving liquid it is convected in the flow direction and retarded in the counter-flow direction. Fig. 2 depicts the air-water stratified flow inside the horizontal tube of the two-phase flow section. A pair of ultrasonic transducers, *T1* and *T2*, were placed outside tube wall on the water side. Each transducer alternatively sends and receives an ultrasonic beam traveling through the water, which is reflected twice by the air-water interface. The difference in the transit-time between the pair of the transducers can be measured and is used to calculate the mean velocity of water along the ultrasonic path *s*. Provided that one knows the relationship between the mean water velocity along the path *s* and the mean water velocity in the cross section, the technique can be used to determine the water flowrate (Lynnworth and Magori, 1999).

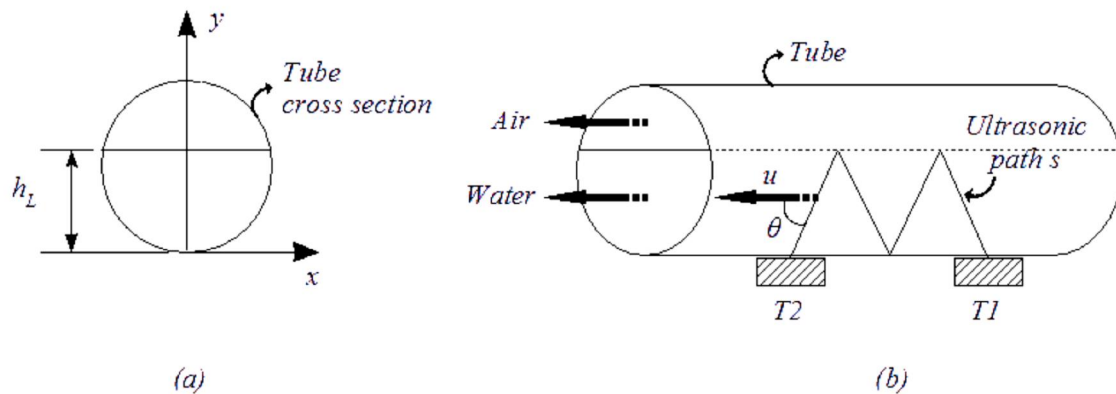


Figure 2. Schematic of a W-path contrapropagating two-phase ultrasonic flowmeter

If the ultrasonic beam is considered as a ray at a fixed angle  $\theta$  across the water of velocity profile  $u$ , in a short time  $dt$  it travels a distance  $ds$  from transducer *T1* to transducer *T2* and

$$\frac{ds}{dt} = c_w + u \cos \theta \quad (1)$$

where  $c_w$  is the stationary sound speed in the water and  $u \cos \theta$  is the component of water velocity in the  $s$  direction, as shown in Fig. (2b). Splitting the path  $s$  into  $s1$ ,  $s2$ ,  $s3$  and  $s4$  according to the transducer which is in contact with the pipe, namely  $s1$  is from *T1* to the air-water interface,  $s2$  is from air-water interface to the tube wall-water interface,  $s3$  is from tube wall-water interface to the air-water interface and  $s4$  is from air-water interface to *T2*, it follows that

$$dt = \frac{dy}{(c_w + u \cos \theta) \sin \theta} \quad (2)$$

for the path  $s1$  since the  $s$  direction is related to the co-ordinate  $y$  by  $\frac{dy}{ds} = \sin \theta$ . For the path  $s2$  the time interval consists of the

$$dt = \frac{-dy}{(c_w + u \cos \theta) \sin \theta} \quad (3)$$

since  $\frac{dy}{ds} = -\sin \theta$  in that case. For the paths  $s3$  and  $s4$  the time intervals are identical to that for  $s1$  and  $s2$ , respectively.

Thus, integrating Eqs. (2) and (3) along the paths  $s$  we obtain the following expressions for the total transit time  $t_{T1-T2}$  from the  $T1$  to the  $T2$  transducer:

$$\Delta t_{T1-T2} = 4 \int_0^{h_L} \frac{dy}{(c_w + u \cos \theta) \sin \theta} \quad (4)$$

The ultrasonic beam travels back from the  $T2$  to the  $T1$  transducer, being retarded by the water flow. The total transit time  $t_{T2-T1}$  for the backward ultrasonic emission is obtained with a similar reasoning. The difference between backward and upward ultrasonic emissions is given by:

$$\Delta t_{T2-T1} - \Delta t_{T1-T2} = \frac{4}{\sin \theta} \int_0^{h_L} \left[ \frac{1}{(c_w - u \cos \theta)} - \frac{1}{(c_w + u \cos \theta)} \right] dy \quad (5)$$

In most practical applications we have  $c_w \gg u$ , which implies that  $t_{T1-T2} \cong t_{T2-T1}$ . For the geometrical configuration shown in Fig. (2) it follows that  $c_w$  is closely approximated by

$$c_w = \frac{4h_L}{\sin \theta \Delta t_m} \quad (6)$$

where  $\Delta t_m = \frac{\Delta t_{T1-T2} + \Delta t_{T2-T1}}{2}$ . Now, with the condition  $c_w \gg u$  and introducing Eq. (6), Eq. (5) reduces to

$$\frac{\Delta t_{T2-T1} - \Delta t_{T1-T2}}{\Delta t_m^2} \frac{h_L}{\sin \theta \cos \theta} = u_{line} \quad (7)$$

where  $u_{line}$  is the mean water velocity along the  $y$  co-ordinate,

$$u_{line} = \frac{1}{h_L} \int_0^{h_L} u dy \quad (8)$$

Thus, it can be seen that the ultrasonic flowmeter performs a measurement along the ultrasonic path  $s$  that is related to the co-ordinate  $y$  through the angle  $\theta$ . It can be seen also that the sound speed in the water does not play any role in Eq. (7) which makes the method insensitive to sound speed variations with water pressure and temperature.

On the other hand, in order to measure the water flow rate, it is necessary to know the mean velocity over the area occupied by the water, namely

$$u_{area} = \frac{1}{A_L} \int_{A_L} u dA \quad (9)$$

where  $A_L$  is the fraction of the pipe cross section occupied by the water. The conversion of the velocity  $u_{line}$  into the velocity  $u_{area}$  is obtained by a correction factor called the hydraulic factor, commonly represented by  $K_h$  and defined as

$$K_h = \frac{u_{line}}{u_{area}} \quad (10)$$

A solution for the water velocity profile along  $h_L$ , as defined by the Eq. (8) and over the area occupied by the water as defined by the Eq. (9) respectively, can be obtained numerically. This solution can be used to determine the hydraulic factor according the Eq. (10). This may be accomplished by modeling the two-phase stratified flow as it has been proposed by De Sampaio *et al.* (2006). A brief description of this model is given.

Consider the domains showed in the Fig. 3. If we suppose a fully developed air-water stratified flow with the interface between the phases as a flat plane thus, the Reynolds averaged Navier-Stokes equations with the  $k$ -turbulence model can describe the flow in both phases:

$$\nabla \cdot (A_i \nabla u) - \frac{dp}{dz} = 0 \quad (11)$$

$$\nabla \cdot (B_i \nabla \kappa) - \beta_2 \rho_i \kappa \omega + S_i = 0 \quad (12)$$

$$\nabla \cdot (C_i \nabla \omega) - \beta_1 \rho_i \omega^2 + \frac{\alpha_1 \omega}{\kappa} S_i = 0 \quad (13)$$

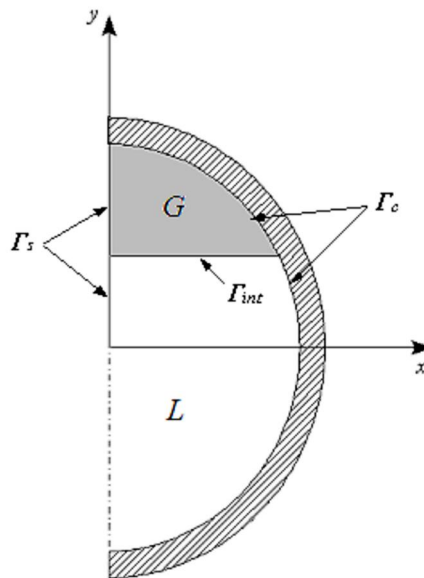


Figure 3. Domains for the physical-mathematical model of the air-water stratified flow

The terms in Eqs. (11) ó (13) are  $A_i = \mu_i + \mu_{ti}$ ,  $B_i = \mu_i + \sigma_2 \mu_{ti}$ ,  $C_i = \mu_i + \sigma_1 \mu_{ti}$ ,  $S_i = A_i \nabla u \cdot \nabla u$ , and  $\mu_{ti} = \alpha_2 \rho_i \kappa / \omega$  where  $k$  is the kinetic energy,  $\omega$  is the energy dissipation,  $\mu_{ti}$  is the eddy viscosity and  $\alpha_1, \alpha_2, \beta_1, \beta_2, \sigma_1, \sigma_2$  are the  $k$ -model parameters.  $dp/dz$  is the pressure loss along the co-ordinate  $z$  (perpendicular to the paper sheet), and  $u$  is the flow velocity. The subscripts 1 and 2 define, respectively, the liquid and gas phases. The boundary and interfacial conditions are defined on the symmetry boundary  $s$  where  $\nabla u \cdot \mathbf{n} = 0$ ,  $\nabla \kappa \cdot \mathbf{n} = 0$  and  $\nabla \omega \cdot \mathbf{n} = 0$ . On the pipe boundary  $c$   $u = 0$ ,  $\kappa = 0$  and  $\omega = \bar{\omega}_{ci}$  with  $\bar{\omega}_{ci} = \frac{2\mu_i}{\beta_0 \rho_i Y_p^2}$ , where  $\beta_0 = 0.072$  is a model constant and  $Y_p$  is the distance of the closest grid point to the pipe wall. At the interface  $int$  the conditions were set up by  $\sum_{i=1,2} A_i \nabla u \cdot \mathbf{n}_i = 0$ ,  $\kappa = 0$  and  $\omega = 10^6 u_0 / d$ , where  $d$  is the inner pipe diameter,  $u_0 = Q_L / \left( \frac{\pi d^2}{4} \right)$  and  $Q_L$  is the

liquid flow rate. The solutions for the velocity profile, kinetic energy and energy dissipation are obtained in both phases, by using an iterative process combining two numerical techniques. A solution algorithm performs a numerical integration of the water velocity profile and the results are used to determine the hydraulic factor according the Eq. (10). More detailed information about the model can be found in De Sampaio *et al.* (2007) and in De Sampaio *et al.* (2008).

#### 4. EXPERIMENTAL PROCEDURES AND RESULTS

The CPUF was the main instrumentation measuring the liquid flow rates in all the experiments described in this work. The CPUF factory calibration plots are showed in the Fig. 4 for a 1 in. tube. It can be seen that for the water flow rate measurements obtained with the CPUF in two-phase flow section, the expected uncertainties are:  $\pm 3\%$  for a water inlet flow rate of 0.2 m<sup>3</sup>/h, and  $\pm 2\%$  for a water inlet flow rate of 0.5 m<sup>3</sup>/h. A whole uncertainty of 1%, as related by the factory, is retained for a flow rate greater than 1.0 m<sup>3</sup>/h only.

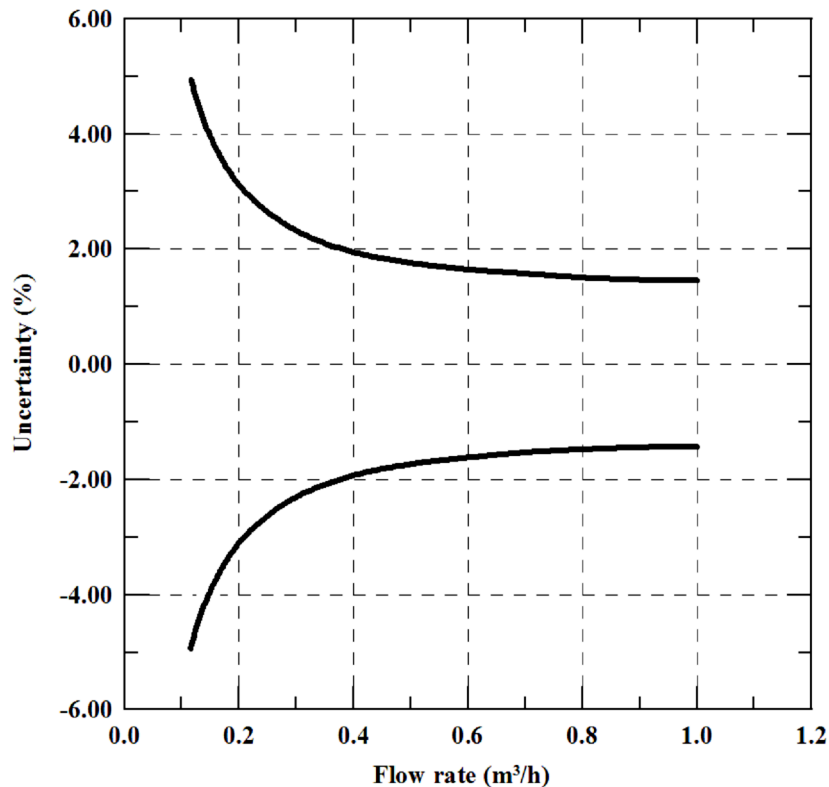


Figure 4. CPUF factory uncertainty measurement as a function of flow rate for a 1 in. tube (Ultraflux, 1998)

The water level estimated at dynamic stratified two-phase flow by PEU is shown in Fig. 5. These water levels are the key to place the CPUF transducers at the appropriate distance between them. This guarantees that all the ultrasonic signals, after a double reflection on the interfaces air-water, will strike both transducers. To determine the water levels inside the two-phase flow section, a series of ultrasonic signals were acquired and recorded using the PEU system. The level could be estimated at each pair air-water inlet flow rate, as follows:

$$h_L = c_w \frac{\Delta t}{2} \tag{14}$$

where  $\Delta t$  is the transit time from the tube wall-water interface to water-air interface, and back to tube wall-water.  $c_w$  was 1,492 m/s for an average water temperature of 25° C, monitored by resistance thermometers. The data acquisition software determined the transit time between those reflection paths which could be inserted into Eq. (1) for estimation of the water level  $h_L$ . The averaged water levels obtained are shown in Tab. 1.

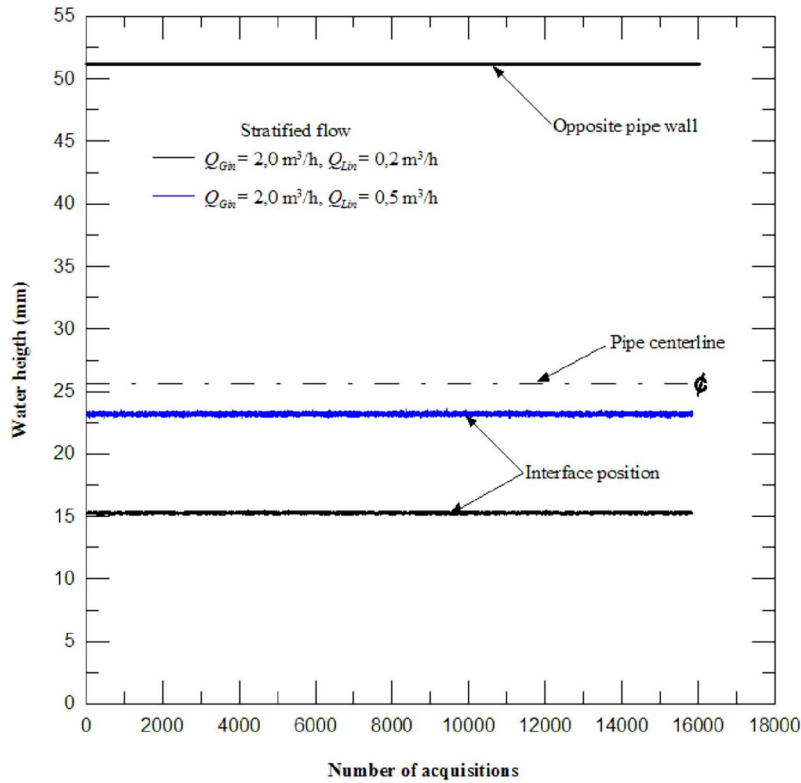


Figure 5. PEU water level measurements

The corrected CPUF measurements as a function of the acquisition time, in the two-phase flow section, can be seen in Figs. 6-7 for one inlet air flow rate:  $Q_{Gin} = 2.0 \text{ m}^3/\text{h}$ ; and two inlet water flow rates:  $Q_{Lin} = 0.2 \text{ m}^3/\text{h}$  and  $0.5 \text{ m}^3/\text{h}$ . It was observed that the CPUF measurements presented a more intensive fluctuations around the average water flow rate of  $0.2 \text{ m}^3/\text{h}$  than the flow rate of  $0.5 \text{ m}^3/\text{h}$ . This behaviour indicates that the CPUF performance, at low flow rates, may differ from the expected factory calibration data shown in Fig. 4. The average water flow rates were estimated, from the measurements presented in Figs. 6-7, by applying a correction on the hydraulic factor and on the flow area.

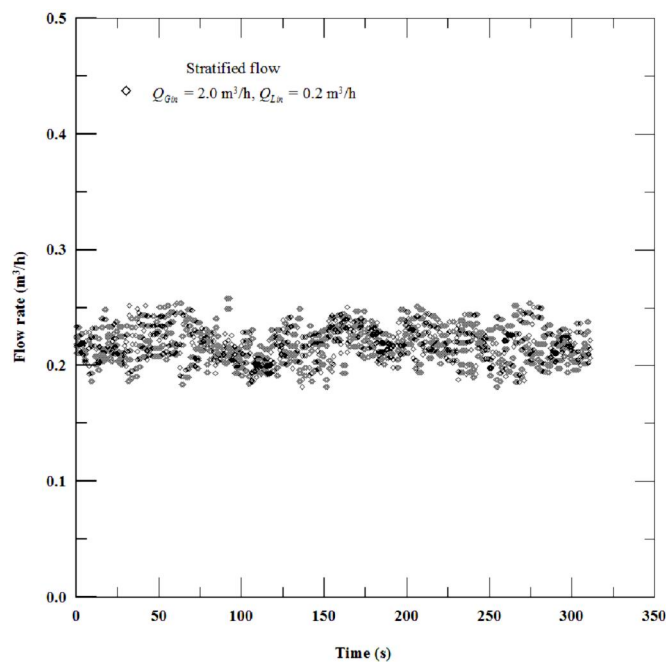


Figure 6. Corrected CPUF water flow rates in the two-phase section, for  $Q_{Gin} = 2.0 \text{ m}^3/\text{h}$  and  $Q_{Lin} = 0.2 \text{ m}^3/\text{h}$ .

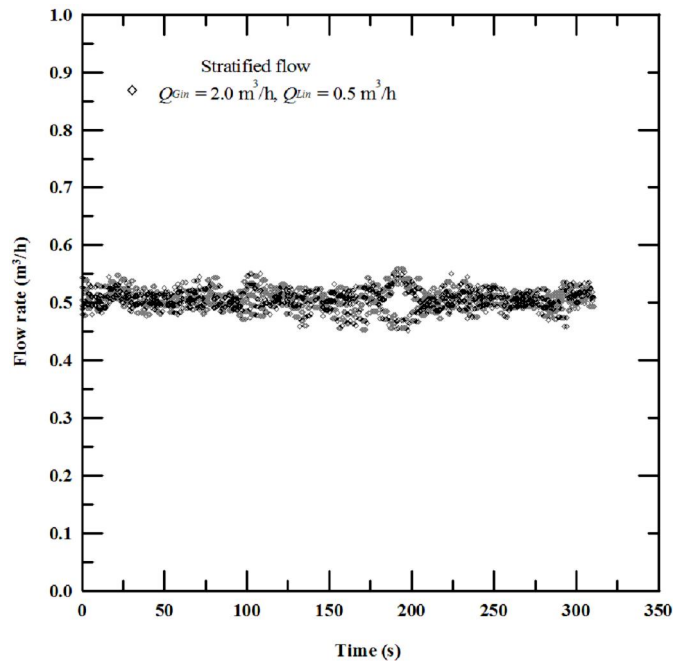


Figure 7. Corrected CPUF water flow rates in the two-phase section, for  $Q_{Gin} = 2.0 \text{ m}^3/\text{h}$  and  $Q_{Lin} = 0.5 \text{ m}^3/\text{h}$ .

The procedure can be better understood looking at the Fig. 8. The cross sectional area occupied by the water is the

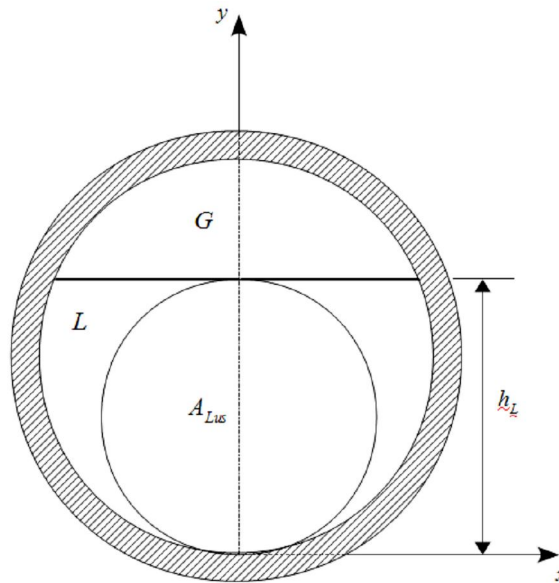


Figure 8. Cross sectional view of the two-phase flow section.

circular segment defined by the level  $h_L$ . However, the area which is used by the CPUF processor to calculate the flow rate is the circle of diameter  $h_L$ . Thus, the corrected flow rate is given by:

$$Q_L^* = \frac{K_{h\_factory}}{K_{h\_numerical}} \frac{A_L}{A_{Lus}} Q_{Lus} \tag{15}$$



where  $A_{Lus} = \pi \frac{h_L^2}{4}$ ,  $Q_{Lus}$  is the water flow rate measured by the CPUF and the  $K_h$  correction  $\frac{K_{h\_factory}}{K_{h\_numerical}}$  can be derived from the Eq. (10).  $K_{h\_factory}$  is automatically calculated by the CPUF as a function of the Reynolds number, based on the area  $A_{Lus}$ , in the case of a turbulent flow. When the flow is laminar, the user can force  $K_{h\_factory}$  to the value of 1.33, (Ultraflux, 1998). On the other hand  $K_{h\_numerical}$  is determined by the physical-mathematical model.

In Tab. 1 are presented the inlet flow rates used in the experiments ( $Q_{Gin}$  and  $Q_{Lin}$ ), the water levels measured by PEU ( $h_L$ ), the numerical  $K_h$  and the average  $Q_L^*$ . All experiments were carried out with water at 1.10 bar and 25° C.

Table1. Experimental data.

$Q_{Gin}$ (m <sup>3</sup> /h)	$Q_{Lin}$ (m <sup>3</sup> /h)	$h_L$ average (mm)	$K_h$ (numerical)	$Q_L^*$ average (m <sup>3</sup> /h)
2.0	0.2	15.3	1.239	0.218
2.0	0.5	23.2	1.184	0.506

Applying the mass conservation principle in the water,

$$\rho_{Lin} Q_{Lin} = \rho_L Q_L^* \quad (16)$$

In general the water can be considered as incompressible at isothermal conditions, thus

$$\rho_{Lin} = \rho_L \quad (17)$$

which implies that

$$Q_{Lin} = Q_L^* \quad (18)$$

Taking into account the average flow values, at  $Q_{Lin} = 0.2$  m<sup>3</sup>/h, the CPUF measurements over predicted the rotameter measurements by 0.018 m<sup>3</sup>/h (+ 9%). At  $Q_{Lin} = 0.5$  m<sup>3</sup>/h, the CPUF over predicted the rotameter by 0.006 m<sup>3</sup>/h (+1.2%). These results show that the proposed correction scheme given by Eq.(15), with the numerical  $K_h$  computed via the physical-mathematical model, have rendered the CPUF also suitable to measure the water flow rate in a stratified two-phase air-water flow.

## 5. CONCLUSIONS

An experimental work was conducted to measure the water level and flow rate in a horizontal two-phase air-water flow section using a hybrid ultrasonic technique formed by a contrapropagating ultrasonic flowmeter (CPUF), a single transducer pulse-echo ultrasonic method (PEU) and a physical-mathematical model. The following conclusions could be deduced:

- the PEU system was able to determine the water level, a key to achieve the water flow rate inside the two-phase section for two air-water inlet flow rates.
- the water level given by PEU allowed to place the CPUF transducers in a right way such that they were able to detect the air-water interface. By making the correction indicated by Eq. (15), it has been possible to measure the water flow rate. Note that the numerical  $K_h$  is calculated using the physical-mathematical model.
- considering that the water rotameter has an uncertainty of  $\pm 3\%$ , a comparison between the rotameter measurements and the average CPUF measurements (in the water portion of the horizontal two-phase flow section), show uncertainties close to expected values according the factory calibration data for a 1 in. diameter tube, since the water level was situated in this range.
- the preliminaries results of the present work indicate that the proposed methodology is suitable for a stratified air-water flow measurement using a single-phase CPUF.

## 6. ACKNOWLEDGEMENTS

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